A Non-Fickian Mixing Model for Stratified Turbulent Flows

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LONG-TERM GOALS

The long term goal of this project is to develop a better understanding of oceanic processes in the range of 100 m to 10 km, in the so-called submesoscale range. In particular, it is important to explore and find out whether and what type of submesoscale instabilities exist, how they are connected to both larger scale and smaller scale motions, and to what extent they influence transport processes in the ocean. Another important objective of this project is to test how well subgrid-scale (SGS) models for large eddy simulations (LES) work in the presence of backward energy cascade that may be characteristic in submesoscale motions. A long term objective of this effort would be to improve the predictive skill of the Navy numerical models for submesoscale transport in the ocean.

OBJECTIVES

My main objective has been to model upper ocean mixed layer instabilities, investigate their behavior and try to develop sampling strategies using synthetic drifters and tracers prior to the first LatMix cruises. In addition, modeling help with data analysis is planned.

APPROACH

The work is based on LES using the non-hydrostatic spectral element model Nek5000 as well as field data. Also, software has been developed in order to automatically download and make available MODIS raw SST data over the selected region in the first LatMix cruise.

WORK COMPLETED

I have completed work on ten papers (see Publications section) under the support of the LatMix project. Of these, two (Özgökmen et al., 2011; Özgökmen and Fischer, 2012) contain a detailed analysis of mixed layer instability (MLI) with particular emphasis on sampling strategies using LES. Two papers focus on subgrid-scale models, in LES (Berselli et al., 2011) and in ocean models (Marques and Özgökmen, 2012). Our approach in Özgökmen et al. (2012) is perhaps the first truly multi-scale LES aiming to dissect the interaction between the submesoscale MLI and deep mesoscale baroclinic instability, and how their multi-scale signature can be detected on the basis of scale-

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dependent relative dispersion plots. I also investigated the observation periods needed for the effects of submesoscale and mesoscale-induced dispersion to show up in these plots. The study by Mensa et al. (2013) is on the seasonality of submesoscale features in the Gulf Stream from realistic, multiple resolution HYCOM simulations, and how a combination of MLI and frontogenesis act to form these features. In Schroeder et al (2012), we summarize results from a targeted drifter launch at a coastal frontal zone. In Haza et al. (2012), we evaluate two different classes of subgrid-scale parameterizations for Lagrangian dispersion in HYCOM for the North Atlantic in order to compensate for the effect of enhanced dispersion over submesoscale regime that is typically missing in mesoscale eddy resolving models. In Haza et al. (2013), the effect of drifter position errors on the estimates of relative dispersion over the submesoscales is quantified. Griffa et al. (2013) is an invited review paper prepared for the special DSR-II issue for 75th birthday of Thomas Rossby, in which I have included some of my mixed-layer instability results as well as a compilation of relative dispersion estimates for the upper ocean.

RESULTS

1) Seasonality of Submesoscale Flows in the Gulf Stream Region:

In this study, results from a realistic high-resolution (HR) simulation of the region of the Gulf Stream recirculation are presented, with the goal of investigating SM processes in the mixed layer and their seasonality. Results show that during the winter season, deep vertical recirculations are observed to develop associated to fronts outcropping from mesoscale eddies and rings into the mixed layer. Mixed-layer instabilities (MLIs) are generated at these fronts, leading to the formation of a vigorous submesoscale field. During summer, on the other hand, the occurrence of vertical recirculations and MLIs appear damped, and the submesoscale (SM) field is much weaker. The characteristics of the mixed layer flow and the occurrence of SM features have been quantitatively characterized in statistical terms. SM features, with scales of the order of the mixed layer Rossby radius, appear characterized during winter by a clear deviation from geostrophy, high Rossby number, with prevalently positive vorticity, and significant divergence. Results of the HR simulations are compared to results from the (low-resolution) LR simulation where submesoscale features are not resolved. In the LR results, seasonality of the mixed layer flow is much reduced, and the field is dominated by mesoscale during the whole year, with relatively small deviations from geostrophy and a quasi-2D behavior. We then investigate the main environmental parameters that control the observed SM seasonality, building on previous results from idealized numerical studies and realistic simulation (Özgökmen et al. 2011; Boccaletti et al. 2007; Capet et al. 2008a,b,c,d; Fox-Kemper and Ferrari 2008; Fox-Kemper et al. 2008; Molemaker et al. 2010). The flow field is filtered to separate meso and larger scales from SM. Isolating the SM anomalies allows to apply the scaling of the total SM vertical buoyancy flux in the mixed layer, PK, proposed by (Fox-Kemper et al. 2008). PK quantifies the APE release associated to MLIs and can be considered as a measure of the presence of SM features in the field. The scaling by Fox-Kemper et al. (2008) and Capet et al. (2008a) links PK with the presence of mesoscale surface lateral gradients in the mixed layer, indicative of surface fronts, and with the magnitude of mixed layer depth MLD. Direct testing with our results shows that the scaling is appropriate, following the same seasonal variations as the observed PK. The governing factor appears to be MLD, while horizontal gradients appear present during the whole year because of the presence of mesoscale eddies and rings. This result is different from what was obtained by Capet et al. (2008a) in the Argentinian Shelf, where the seasonality of both horizontal gradients and MLD contributes to the scaling, and both are induced by atmospheric forcing. In our case, atmospheric fluxes and wind forcing are still the cause of SM occurrence, but mostly through their action on MLD. While surface fronts are always available, the deep MLD during winter provides a much greater reservoir of APE, which allows MLIs to develop a vigorous SM field.

The importance of MLIs on the large scales is suggested by the comparison between the mixed layer in HR and LR. The mixed layer in HR is shallower than in LR of approximately 50 m, i.e., of a significant ~ 25 %, suggesting that the restratification induced by SM is the cause of mixed layer shoaling.

We notice that this finding is different from what was shown in Capet et al. (2008b,c,d) in the California upwelling simulations, where MLD did not change significantly between HR and LR simulations. As suggested by Capet et al. (2008b), this is likely due to their numerical setting characterized by constant forcing, which allows destratifying effects by vertical mixing to counteract the stratifying effects of MLIs. In our simulations, instead, atmospheric variability and mesoscale-induced frontal variability appear to maintain MLI activity and their stratifying effects.

Overall the results provide a first picture of SM dynamics in the complex GS region, characterized by strong nonlinear mesoscale interactions. One of the main results is that MLIs appear to be one of the main mechanisms leading to a vigorous winter SM field, mostly due to deepening of the mixed layer and increased APE reservoir. MLI structure and their scaling appear well captured by the parametrization proposed by Fox-Kemper et al. (2008), indicating that the relationship is appropriate even in this complex and mesoscale-dominated area.

2) Submesoscale Transport in Star Eddies:
Star eddies have been observed from MODIS SST images in both the summer 2011 and winter 2012 LatMix cruises. I have conducted LES modeling in order to explore why and how these perturbations grow along the periphery of cyclonic eddies and narrowed down the reason to mixed layer frontal instabilities. In other words, cyclonic eddies protrude through the mixed layer and mesoscale eddy boundaries also form fronts in the mixed layer, which then become unstable via MLIs (Fig. 3, upper panel). Even 20 m deep mixed layers are able to create significant submesoscale movement at the surface signature of the eddy.

It is observed that these simulations have naturally generated significant amounts of inertia gravity waves, which are usually not very easy to obtain. These waves are then used to explore whether 40 m wavelength filaments seen in the tracer distributions observed from LIDAR during summer 2011 cruise can result from such a field. This is a very original problem in that not only most models do not resolve inertia gravity waves due to many computational issues (resolution, lacking dynamics or to many parameterizations, hydrostatic approximation, artificial generation mechanisms, inability of the waves to mature and saturate before numerical dissipation, etc.), but also 3D dispersion patterns by waves is in general not a problem that has been studied. Tracer patches have been continuously injected at constant depths and with sizes that are characteristic in the field, namely 40m wide and 2m thick (which is quite challenging numerically). I have obtained some patterns that resemble the filamentation in the field (Fig. 3, lower panel), but far more work is needed in this area.

Transport characteristics in star eddies are investigated using a 1/100 degree HYCOM simulation (Fig. 4, upper left). The full flow field is seeded with 1 million synthetic particles that are advected in 2D at the surface only and it is found that these lead to a very patchy pattern (Fig. 4, upper right). When the horizontal divergence is removed, the advection gives results that are far more characteristic of what is known from geophysical dynamical systems applications, namely elliptic regions that trap the particles and hyperbolic regions that stretch them into filaments (Fig. 4, lower left). Finally, geostrophic

velocities are computed from SSH field as these give an indication of how the model would become after assimilating altimeter data. The result shows further reduction in the complexity of the advected particle field (Fig. 4, lower right). Overall, the difference between submesoscale induced transport in the mixed layer and what is obtained by removing this flow field is rather drastic (Fig. 4, left panels). We conclude that submesoscale effects are not just small wiggles superimposed on the mesoscale field but have a first order effect on transport even in the strongest mesoscale features.

3) Anaysis of drifters from LatMix 2011 summer cruise:
Insight on the submesoscale flows is important for any transport prediction problem involving the early stages of tracer dispersion, such as oil spills. Due to the small temporal and spatial scales characterizing submesoscale motions (few hours, 100 m to 10 km), quantification of dispersion is likely to be sensitive to measurement errors in particle position, as well as sampling frequency. The objective of this study is to investigate how observational constraints can affect scale-dependent relative dispersion in the submesoscale range, and how to improve separation of the signal from measurement errors.

In order to develop methodologies to get the most out of data containing errors, synthetic trajectories from two models, namely a large eddy simulation (LES) of an idealized submesoscale flow, and a realistic simulation of the North Atlantic circulation with a 2km horizontal resolution HYCOM are corrupted with noise on particle positions, and then subjected to low-pass filtering and reduced frequency sampling. Scale-dependent Lagrangian measures of two-particle dispersion, mainly the Finite Scale Lyapunov Exponent (FSLE, $\lambda(\delta)$) are used as metrics to determine the effects of these uncertainties on dispersion regimes.

Results show that random position errors generate a $\lambda \sim \delta^{-1}$ regime in the submesoscales. The effect of these errors on the FSLE is found to be proportional to the standard deviation of the position error and inversely proportional to the sampling time. Low-passing or subsampling the trajectories reduce the noise amplitude proportionally to their corresponding periods. A rescaling of FSLE is proposed to help extract the real signal.

The signal of real submesoscale-driven dispersion is found to be less sensitive to low-pass filtering and subsampling. The degree to which FSLE is affected depends on the time scales of the features controlling the relative dispersion at a given spatial scale, and on their impact on the cumulative relative dispersion. The recovered signal is the FSLE of the low-passed trajectories with the smallest filter strength necessary to distinguish noise from real relative dispersion whenever λ becomes higher than predicted for the filtered noise.

Application of this filtering process to the SVP (Surface Velocity Program) drifters with Argos positioning system released during the 2011 Lateral Mixing submesoscale experiment indicates that the measurement noise dominates the dispersion regime in FSLE for separation scales δ<3 km (Fig. 5). An expression is provided to help estimate position uncertainties that can be afforded depending on the expected maximum FSLE in the submesoscale regime.

IMPACT/APPLICATIONS

The scales considered in this project represent the range of scale of navy operations and thus anomalous currents and perturbations in the acoustic and optical environment that can affect a variety

of navy operations. Understanding the motion in this range of scales is therefore critical to help improve the predictive capability of the existing Navy models.

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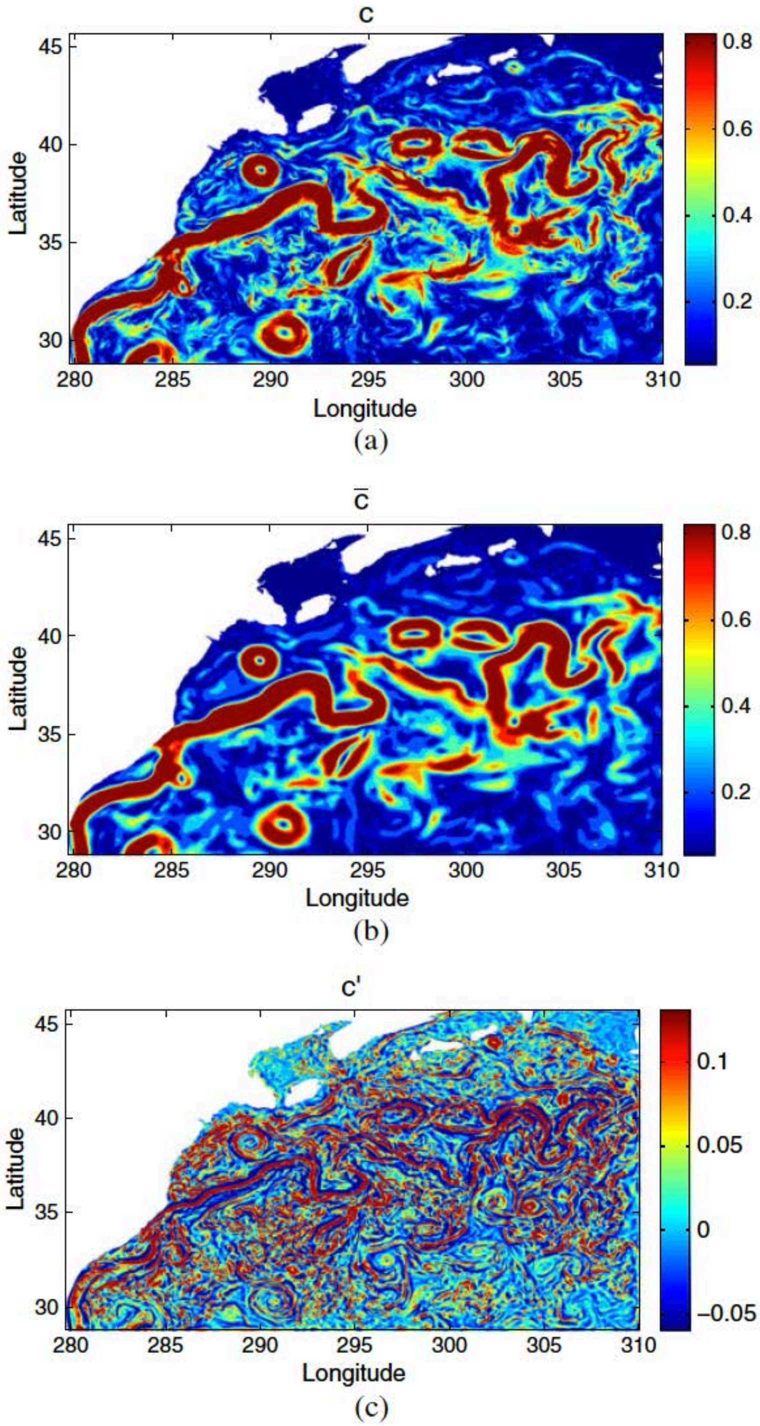
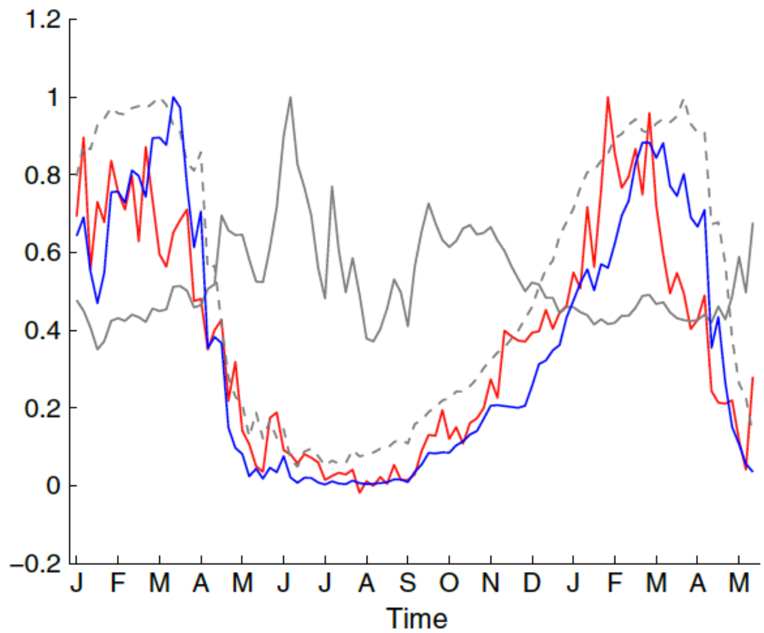


Fig. 1: Total (upper), filtered (middle) and residual/submesoscale (lower panel) speeds from the high-resolution HYCOM simulation (from Mensa et al., 2013).



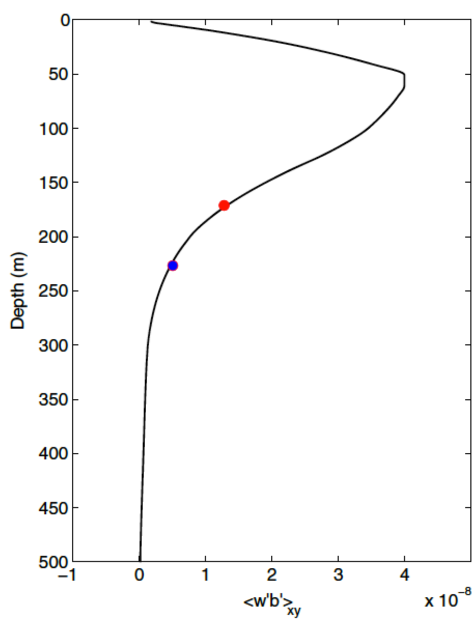


Fig. 2: (Upper panel) Area integrated vertical buoyancy flux at the surface (red), buoyancy gradient (blue) and mixed layer depth (dashed grey) from the high-resolution (HR) HYCOM in the North Atlantic. (Lower panel) Vertical dependence of buoyancy flux in HR during winter season. The dots represent the mixed layer depth for HR (~ 71 m, red dot) and LR (~ 226 m, blue dot) (from Mensa et al., 2013).

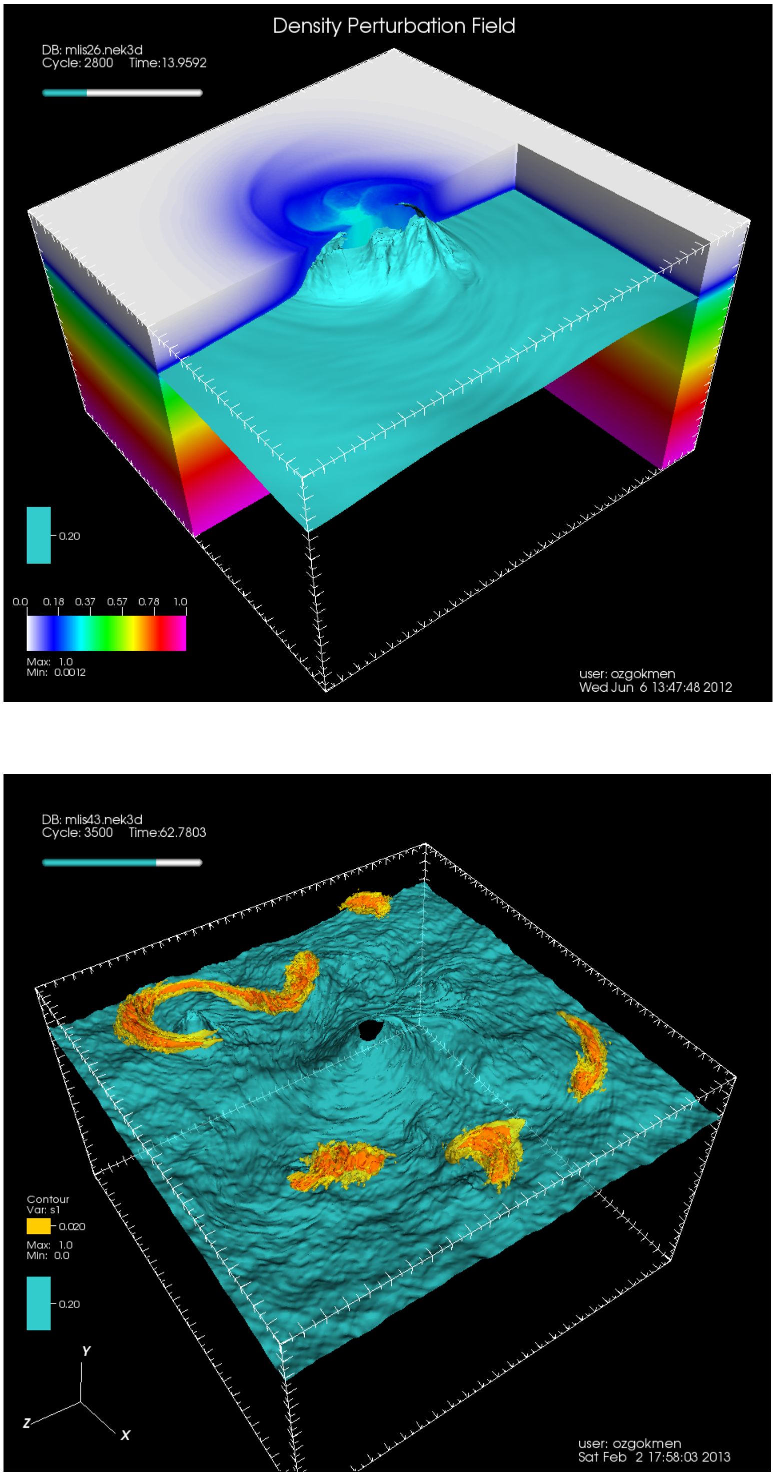


Fig. 3: (Upper panel) LES showing the formation of a star eddy by the interaction of mixed layer front with a cyclonic eddy. The contours indicate various density perturbation values. (Lower panel) Tracer injected at constant depth in the flow field induced by inertia gravity waves in order to explore whether a dominant dispersion pattern would emerge.

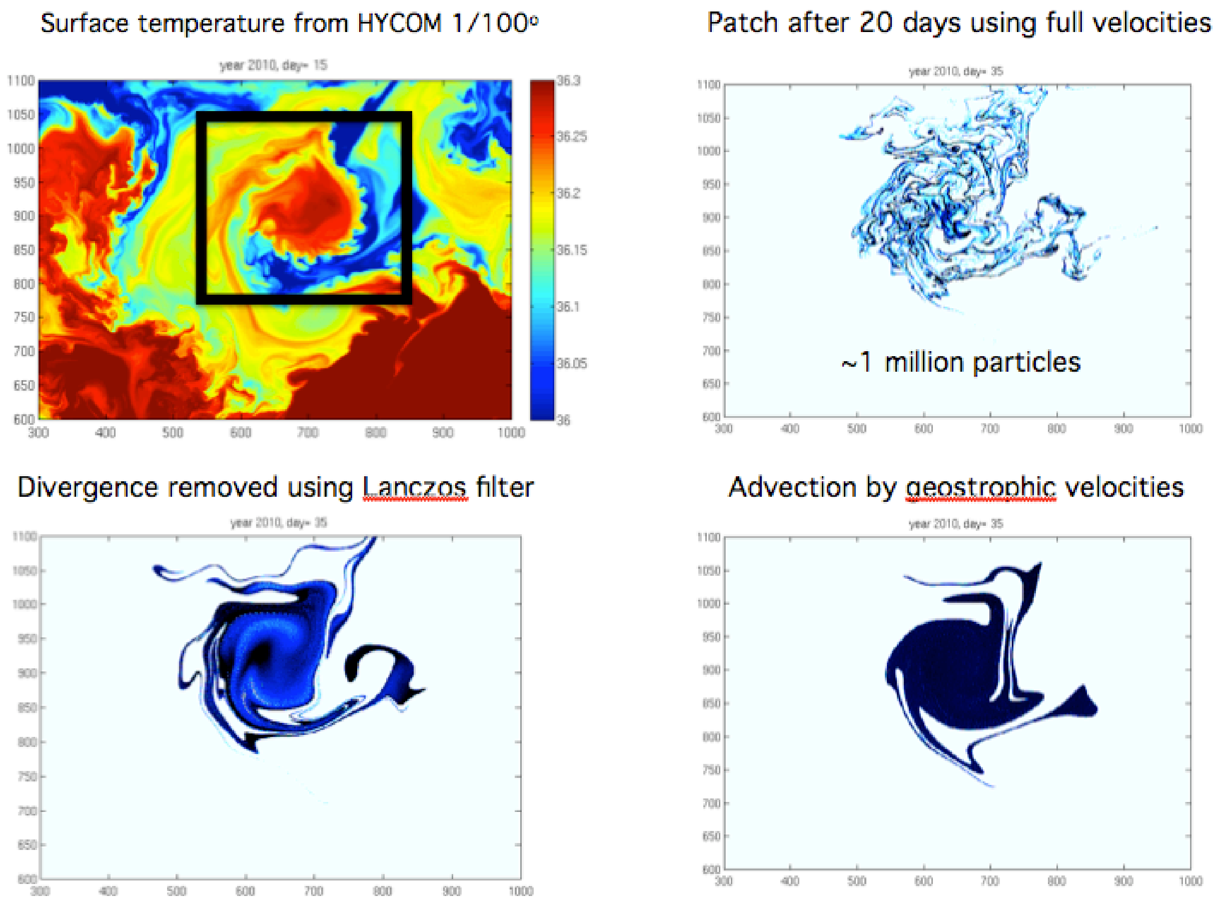


Fig. 4: (Upper left panel) Identification of a star eddy from a very high resolution HYCOM model in free (non-assimilating) mode. (Upper right panel) State of 1 million particles released in the flow field after 20 days of integration. (Lower left panel) Same after the horizontal divergence is removed from the flow field using a Lanczos filter. (Lower right) Particle patch using geostrophic velocities computed from the SSH field.

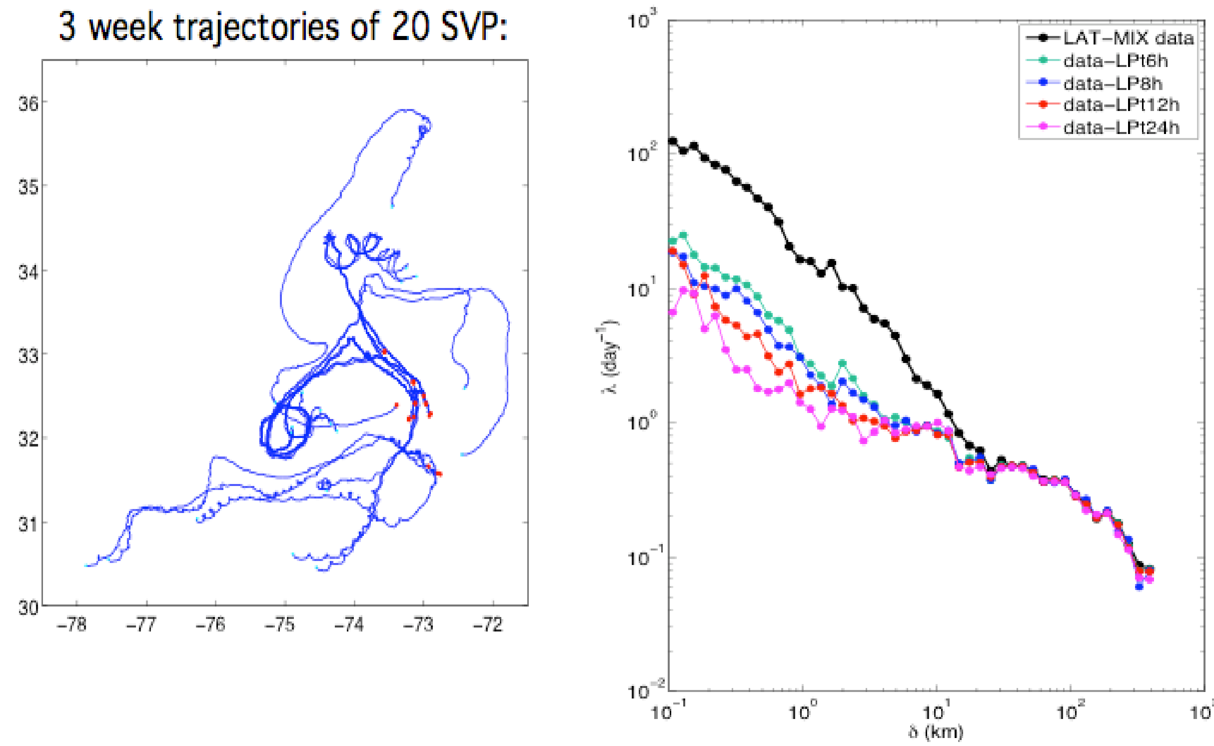


Fig. 5: (Left panel) Trajectories of SVP drifters released during the 2011 summer LatMix experiment. (Left panel) Scale-dependent finite-scale Lyapunov exponent metric indicating the susceptibility of the submesoscale dispersion estimate to time filtering, and implying that large position errors make an accurate calculation not feasible.